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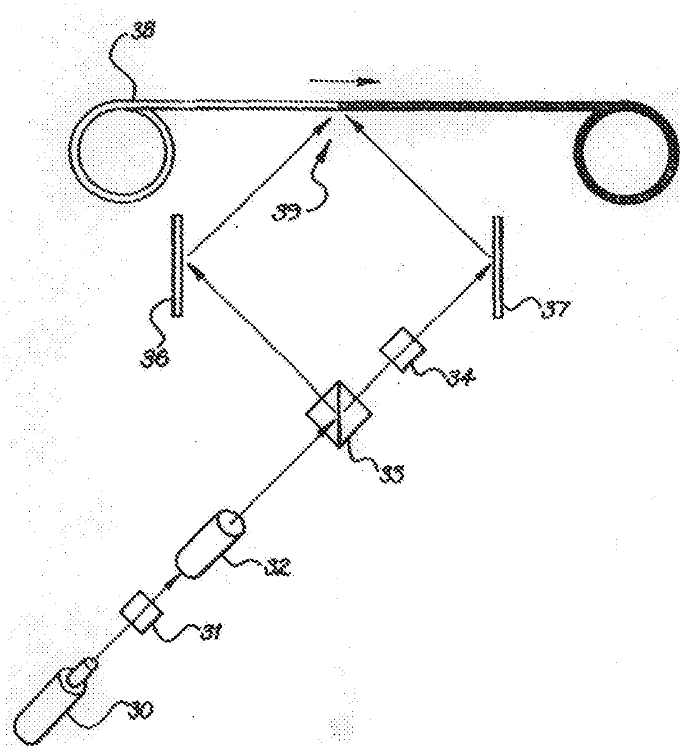
(54) Title: CONTROLLED PHASE DELAY BETWEEN BEAMS FOR WRITING BRAGG GRATINGS

(57) Abstract

At least two beams of light form an interference pattern (39) for writing a grating structure on a photosensitive waveguide (38), where the interference pattern (39) is controlled by modulating the relative phase of the beams. The modulation may be via an electro–optic, magneto–optic, or acousto–optic phase modulator (34), or via a mechanically driven phase modulator (34) comprising a wedge, waveplate or phase mask. In the latter case the phase mask can also act as a beamsplitter (33) for forming the beams. Extended gratings can be written by moving the waveguide (38) while controlling the relative phase shift, and can comprise chirped, apodized and arbitrary grating profiles. Noise can be reduced via an optoelectronic feedback loop. In one embodiment the relative phase is modulated via an electro–optic modulator (32) acting on a polarized beam, which is then split into two beams by a polarisation beamsplitter (33) such that one beam passes through a half–wave plate (34), to form interference pattern (39).



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# CONTROLLED PHASE DELAY BETWEEN BEAMS FOR WRITING BRAGG GRATINGS

## Field of the Invention

The present invention relates to the field of constructing Bragg gratings or the like in UV or like photosensitive waveguides utilizing a UV or like interference pattern.

## Background of the Invention

The present invention is directed to writing gratings or other structures in a photosensitive optical waveguide. The creation of a grating utilizing the interference pattern from two interfering coherent UV beams is well known. This technique for construction of Bragg gratings is fully described in US Patent No. 4,725,110 issued to W H Glenn et. al. and US Patent No. 4,807,950 issued to W H Glenn et. al.

Bragg grating structures have become increasingly useful and the demand for longer and longer grating structures having higher and higher quality properties has lead to the general need to create improved grating structures.

## Summary of the Invention

It is an object of the present invention to provide a method and apparatus for writing extended grating structures in optical waveguides or the like.

In accordance with a first aspect of the present invention, there is provided a method of writing a grating structure on a photosensitive waveguide utilizing at least two overlapping interfering beams of light to form an interference pattern, the method comprising the step of: utilizing at least one modulator in the path of one or more of the beams so as to provide a controlled relative phase delay between the beams so as to thereby control the positions of maxima within the interference pattern so as to further write the grating structure in the photosensitive waveguide.

An extended grating structure can be created by

moving the photosensitive waveguide in a first predetermined direction whilst simultaneously controlling the phase delay so as to impart a predetermined pattern in the waveguide. The at least two overlapping interfering beams are preferably formed from the splitting of a single coherent beam of light so as to form two independent coherent beams of light.

The modulator can comprise one of an electo-optic phase modulator, a magneto-optic phase modulator, a mechanically driven optical phase modulator, a frequency shifter or other form of controllable optical retarder. When using a mechanically driven optical phase modulator it can further comprise an optical phase mask, an optical wedge or an optical waveplate.

The beams are preferably further formed from the reflection of the independent coherent beams around an optical circuit comprising a series of reflection elements. The independent coherent beams are preferably focussed onto the waveguide to improve the spatial resolution of the extended grating structure. The control of the phase delay can be utilized to improve the noise properties of the extended grating structure through utilization of a feedback loop. The feedback loop can be an opto-electonic feedback loop.

The grating can comprise a chirped, and or apodized grating. Indeed the grating can be of an arbitrary predetermined strength, period and phase profile.

In an embodiment, the beams can comprise substantially orthogonal polarization states and the modulator modulates the relative phase delay between the polarization states and the polarization states are preferably aligned subsequent to the modulation.

## Brief Description of the Drawings

Notwithstanding any other forms which may fall within the scope of the present invention, preferred forms of the invention will now be described, by way of example

only, with reference to the accompanying drawings in which:

Fig. 1 illustrates schematically a first embodiment of the present invention;

Fig. 2 illustrates one form of driving of the electro-optic modulator in accordance with the principles of the present invention;

Fig. 3 illustrates an alternative embodiment of the present invention; and

Fig. 4 illustrates a further alternative embodiment of the present invention;

Description of Preferred and Other Embodiments

Turning initially to Fig. 1, there is illustrated the arrangement 1 of a preferred embodiment which is similar to the aforementioned arrangement of Glenn et. al. with the additional inclusion of an optical phase modulating element 2. The basic operation of the arrangement of Fig. 1 is that a UV source 3 undergoes beam splitting by beamsplitter 4 so as to form two coherent beams 5, 6. A phase mask placed appropriately into the setup can be used to split the beam. Each beam is reflected by a suitably positioned mirror eg. 7, 8 so that the beams interfere in the region 9. In this region, there is placed a photosensitive optical waveguide 10 on which an extended grating structure is to be written. The essence of the preferred embodiment is to utilize the phase modulator 2 so as to modulate the relative phase difference between the two beams 5, 6 at the point of interference 9 such that the interference pattern remains static in the reference frame of the optical waveguide 10 as the waveguide is moved generally in the direction 12. The phase modulator 2 can be an electro-optic modulator of a known type including an ADP, KD*P,BBO crystal type transparent at the UV source wavelength. Suitable electro-optic crystals are available from many optical components manufacturers including Leysop Limited under the model numbers EM200A and EM200K. The modulator operates so as to

provide for a controlled phase delay of the beam 5 relative to the beam 6. In a first example, the control is achieved by setting the level of an input signal given the fibre 10 is moving at a constant velocity. The input signal in this case can comprise a saw tooth wave form as illustrated in Fig. 2, the maximum saw tooth magnitude being set to be equivalent to a $2\pi$ phase delay. The slope of the saw tooth wave form is set so as to closely match the velocity of the changing maxima of the interference pattern to that of the fibre 10.

Hence, prior known mechanical methods of movement of any portion of the apparatus is dispensed with and long or stitched interference patterns can be obtained through the utilization of the phase modulating device 2 to introduce the required optical phase difference between the interfering UV beams 5 and 6. As the phase is invariant with respect to a $2\pi$ change, there is no need to introduce large phase differences thus limiting the required amplitude of the phase change to $2\pi$ and allowing it to operate near the balance point of the interferometer. The electro-optically induced phase change will make the interference pattern move along the fibre as the fibre itself moves and the direction and velocity of the move can be set in accordance with requirements. The saw tooth wave form achieving the effect of ``running lights''.

Electro-optic modulators such as those aforementioned can operate with very low response time and extremely high cut off frequencies. Hence, the saw tooth edge fall can be practically invisible and a near perfect stitch can be achieved. At 6mm per minute scanning speed, the modulation frequency can be about 200Hz.

Further, by applying a differential velocity between the fibre and the pattern or through appropriate control of the phase delay, a wavelength shift with respect to the static case can be obtained. An acceleration or appropriate control of the phase delay can be used to produce a chirp and so on. Apodisation can also be

provided by proper additional modulation of the electro-optic modulator.

The embodiment described has an advantage of having all optical elements static except for the moving fibre. Therefore, it allows for focussing of the interfering beams tightly onto the fibre and achieving spatial resolution reaching fundamental limits (of the order of the UV writing wavelength, the practical limit being the fibre core diameter). The static interferometer arrangement itself leads to reduced phase and amplitude noise of the interference pattern. Additionally, the ability to control the phase and amplitude of the pattern using a feedback loop provides a means to improve the noise properties of the interferometer substantially.

A number of further refinements are possible. For example, in order to accurately match the velocity of the fibre 10 and the electro-optic modulator frequency, a simple scanning Fabry-Perot interferometric sensor can be used to measure the relative positions of the fibre and the interference pattern 9. A high finesse (F) resonator can be used to achieve the accuracy of distance measurements much better than the wavelength of the narrow line width source which would be employed in the sensor.

By scanning the Fabry-Perot at a constant rate or sweeping the laser frequency the position can be precisely (1/2F) determined. To increase the resolution further a conversion of the interferometer into a laser at threshold may be needed. In this case the finesse F of the cavity is close to infinity and the resolution is enhanced. Other types of interferometric sensors such as a Michelson interferometer can be used to accurately determine the fibre position with respect to the interference pattern.

Of course, other arrangements utilizing this principle are possible. For example, the teachings of PCT patent application No. PCT/AU96/00782 by Ouellette et. al. discloses an improved low noise sensitivity inteferometric arrangement which operates on a ``Sagnac loop'' type

arrangement. Turning now to Fig. 3 there is illustrated a modified form of the Ouellette arrangement to incorporate the principles of the present invention. In this modified form, an initial input UV beam 20 is diffracted by phase mask 21 so as to produce two output beams 22, 23. The beam 23 is reflected by mirrors 24, 25 so as to fall upon the fibre 26 in the area 27. Similarly, beam 22 is reflected by mirror 25 and mirror 24 before passing through an electro-optic modulator 28 which modifies the phase of the beam relative to the beam 23. The two beams interfere in the area 27. The phase of the interference patterns can be controlled by the modulator 28 in the same manner as the aforementioned. In this manner, the advantages of the previous Ouellette arrangement can be utilized in a stable mechanical arrangement in that it is not necessary to sweep the beam across the phase mask 21 or perform any other movements other than the electrical modulation of the modulator element 28 whilst forming an extended grating structure. Moreover, the interferometer can be adjusted to operate near its balance point and a low coherence length UV source can be used in the arrangement.

Further, a phase modulator based on a magneto-optic effect could be used instead of an electro-optic modulator. In the Sagnac interferometer arrangement, it can be placed such that both of the interfering beams pass the Faraday cell in opposite directions such that a non-reciprocal controlled relative phase delay is introduced between the counter propagating beams.

Turning now to Fig. 4 there is illustrated an alternative arrangement to incorporate the principles of the present invention. In this arrangement, the output from a UV laser 30 is initially linearly polarized 31 before passing through an electro-optic modulator 32 which modifies the polarization state of the beam. The polarization plane of the UV beam with respect to the birefringent axes of the electro-optic modulator 32 is such that two orthogonal polarization eigenstates with equal

intensities propagate in the modulator, with one of the eignstates being phase modulated while the other one being not. The arrangement uses polarization beam splitter 33 to separate the polarization states and half-wave plate 34 is used to 90 degree rotate the polarization of one of the resulting beams to allow for the interference taking place between the beams. The beams are further reflected by mirrors 36 and 37 so as to fall upon the fibre 38 in the area 39 to produce an interference pattern in conjunction with movement of the fibre 38. The phase of the interference pattern can be controlled by the modulator 32 in the same manner as the aforementioned to produce an extended grating structure.

In a further alternative embodiment, a travelling wave acousto-optic (AO) modulator transparent at the wavelength of the UV source 3 can be used as a modulating element 2 to frequency shift the diffracted light. The interference between the two beams at different frequencies in region 9 will result in a interference pattern travelling at a velocity $v = -\Delta\nu \bullet \Lambda/2$. For example, for $\Delta\nu$=200 Hz frequency shift and $\Lambda$=1$\mu$m interference pattern period the velocity of the pattern is v=6mm/min and the optical waveguide 10 should be translated at this speed in the same direction. No special modulation waveforms need to be applied in this case, with the control parameter being the frequency shift. As most commercial acousto-optic modulators operate in a MHz range, a frequency shift of the second interfering beam may be required to achieve the differential frequency shift in the Hz - kHz range. There may be also need for a minor adjustment compared to the electro-optic modulator arrangement of Fig. 2 as the Bragg angle will vary with the frequency of the applied to the AO modulator signal resulting in a displacement of the diffracted beam. However the effect of this displacement can be reduced by making the setup compact. There could also be a further adjustment since AO modulators may exhibit resonances.

In a modified embodiment, a mechanically driven optical phase modulator can be utilized to control the phase of the interference pattern. An optical phase mask, optical wedge or an optical waveplate can be utilized. The optical phase mask can also have a function of the beamsplitter. The embodiment utilizing the phase mask works for all known phase-mask based interferometer arrangements, such as phase mask direct writing technique, or for a Sagnac interferometer writing technique (such as that due to Ouellette disclosed on PCT application number PCT/AU96/00782) or when utilizing the aforementioned system due to Glenn et. al.

It would be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

We Claim:

1. A method of writing a grating structure on a photosensitive waveguide utilizing at least two overlapping interfering beams of light to form an interference pattern, said method comprising the step of:

utilizing at least one modulator in the optical path so as to provide a controlled relative phase delay between said beams so as to thereby control the positions of maxima within said interference pattern so as to further write said grating structure in said photosensitive waveguide.

2. A method as claimed in claim 1 wherein an extended grating structure is created by moving said photosensitive waveguide in a first predetermined direction whilst simultaneously controlling said phase delay so as to impart a predetermined pattern in said waveguide.

3. A method as claimed in any previous claim wherein said at least two overlapping interfering beams are formed from the splitting of a single coherent beam of light so as to form two independent coherent beams of light.

4. A method as claimed in any previous claim wherein said modulator is utilized before, after or in the process of splitting said beams.

5. A method as claimed in any of claims 1 to 3 wherein said modulator comprises a controllable optical retarder or optical delay line.

6. A method as claimed in any of claims 1 to 4 wherein said modulator is an electo-optic phase modulator.

7. A method as claimed in any of claims 1 to 4 wherein said modulator is a magneto-optic phase modulator.

8. A method as claimed in any of claims 1 to 4 wherein said modulator is a frequency shifter.

9. A method as claimed in any of claim 1 to claim 4 wherein said modulator is a mechanically driven optical phase modulator.

10. A method as claimed in claim 9 wherein said

mechanically driven optical phase modulator comprises an optical phase mask, an optical wedge or an optical waveplate.

11. A method as claimed in claim 3 wherein said beams are further formed from the reflection of said independent coherent beams around an optical circuit comprising a series of reflection elements.

12. A method as claimed in any previous claim wherein said independent coherent beams are focussed onto said waveguide to improve the spatial resolution of said extended grating structure.

13. A method as claimed in any previous claim wherein said control of the phase delay is utilized to improve the noise properties of the extended grating structure through utilization of a feedback loop.

14. A method as claimed in claim 13 wherein said feedback loop is an opto-electonic feedback loop.

15. A method as claimed in any previous claim wherein said grating comprises a chirp grating.

16. A method as claimed in any previous claim wherein said grating is an apodized grating.

17. A method as claimed in any preceding claim wherein said grating includes an arbitrary predetermined strength, period and phase profile.

18. A method as claimed in any preceding claim wherein said beams comprise substantially orthogonal polarization states and said modulator modulates the relative phase delay between said polarization states and said polarization states are aligned subsequent to said modulation.

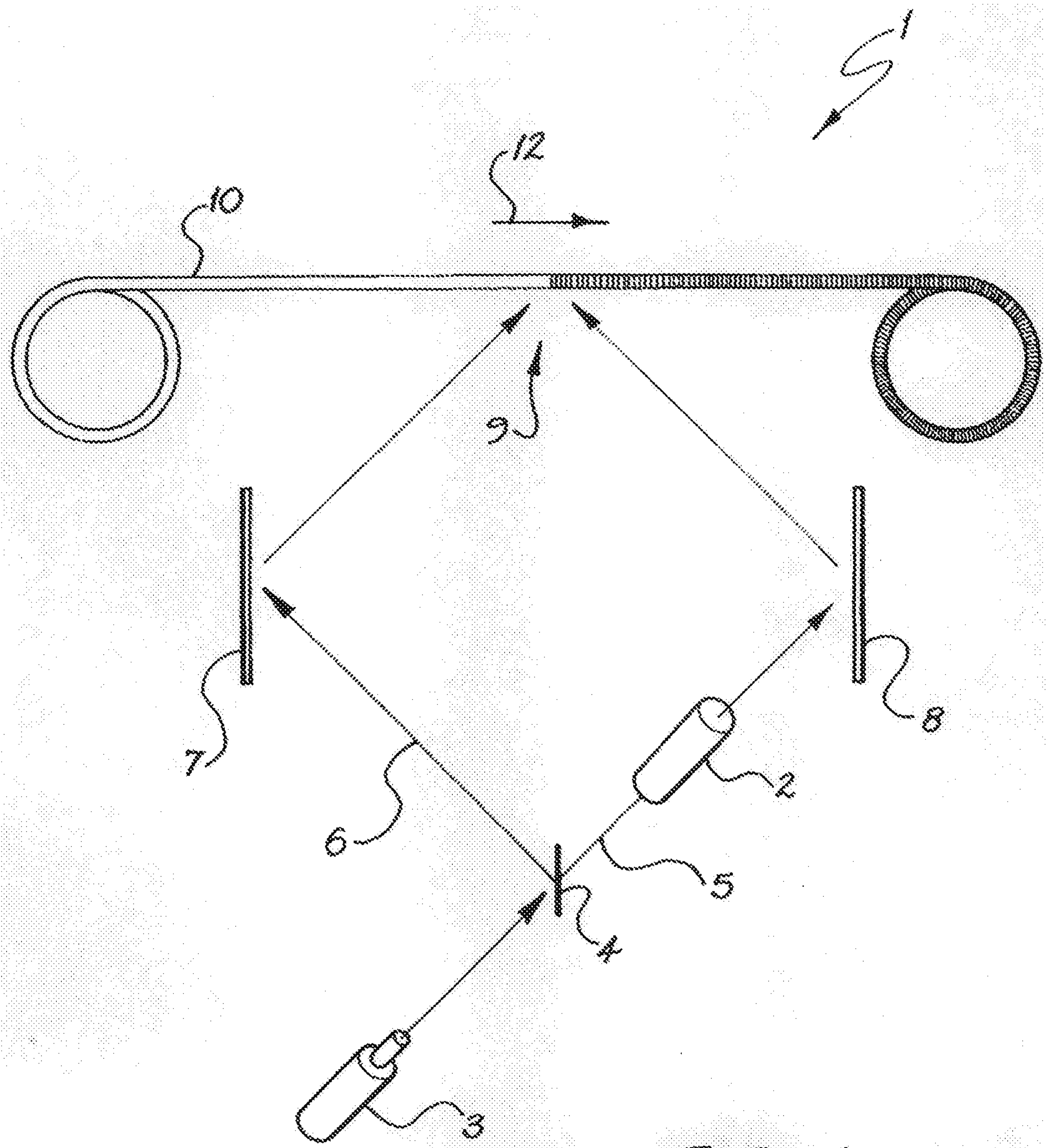


FIG. 1

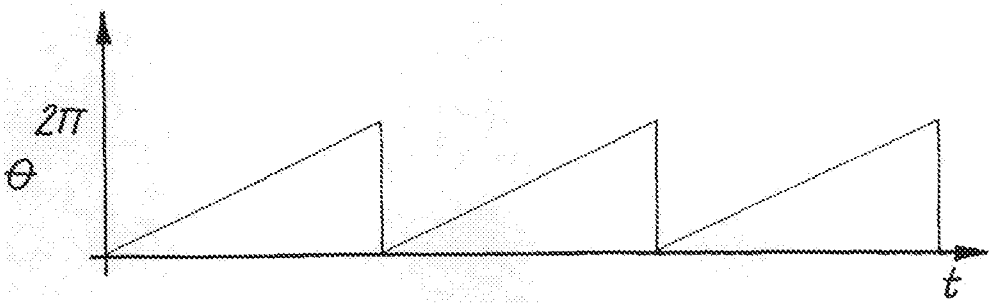


FIG. 2

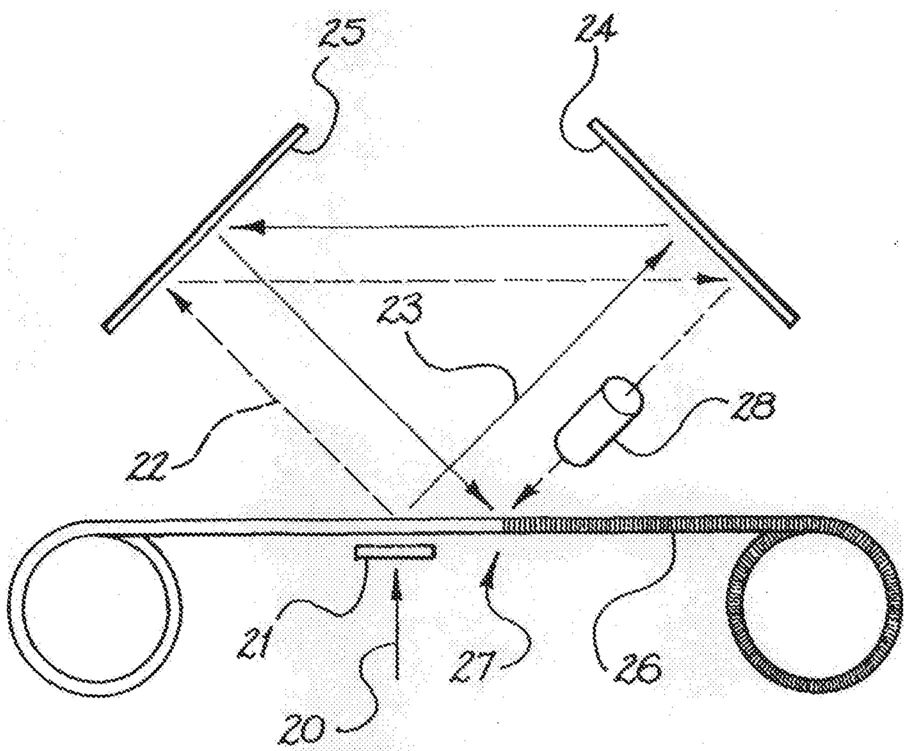


FIG. 3

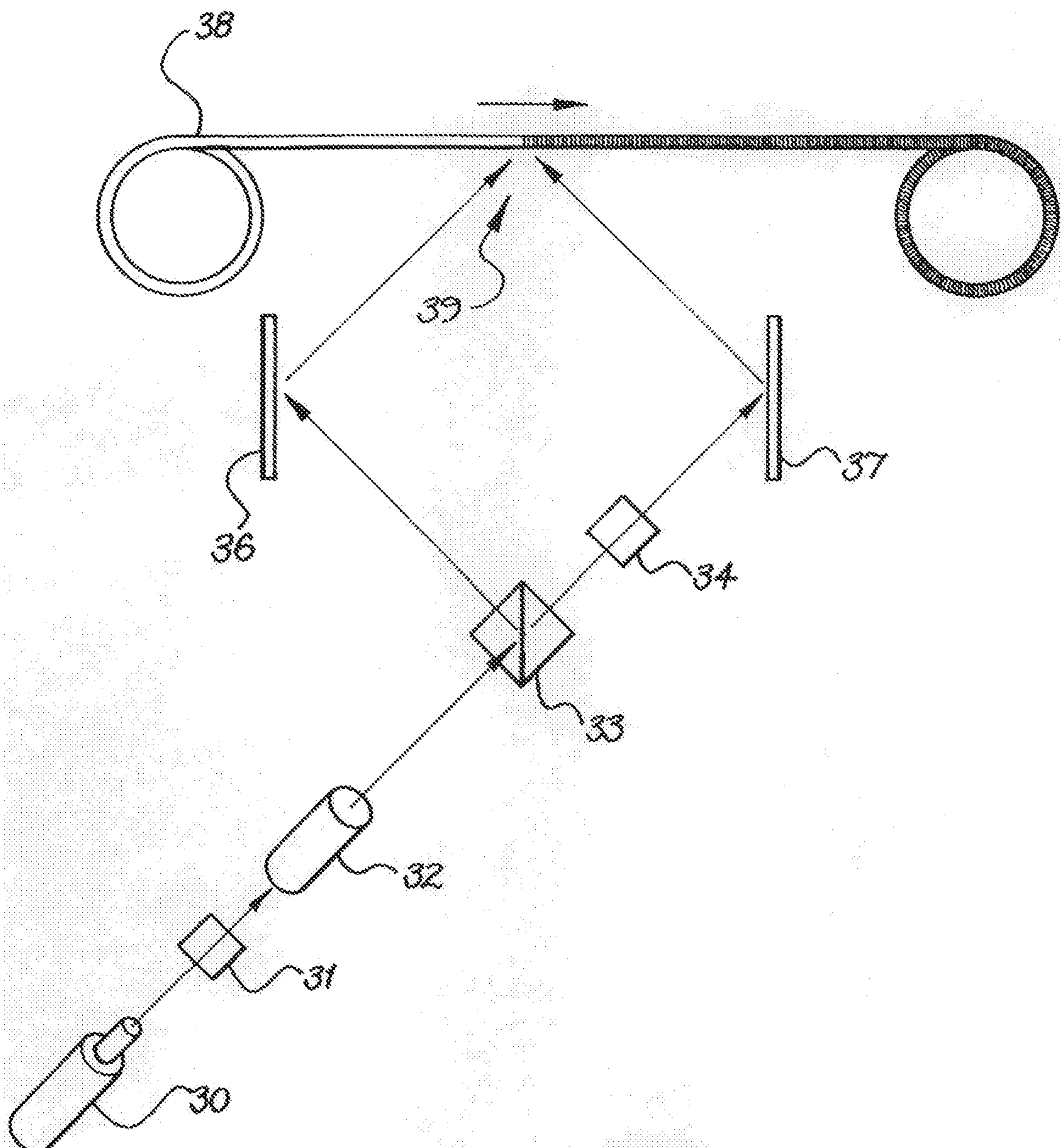


FIG. 4

**INTERNATIONAL SEARCH REPORT**

International application No.
PCT/AU 99/00417

**A. CLASSIFICATION OF SUBJECT MATTER**

Int Cl[6]: G02B6/10, 5/28

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)
G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
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**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| P, X | FR 2768819 A (ALCATEL ALSTHOM COMPAGNIE GENERALE D'ELECTRICITE SOCIETE ANONYME) 26 March 1999<br>Pages 4-6, Figures 1-2 | 1-10, 12-17 |
| X<br>Y | US 5388173 A (GLENN) 7 February 1995<br>Columns 3-7, Figures 1, 7 | 1-7, 9-10, 12, 15-17<br>11 |
| X<br>Y | US 5066133 A (BRIENZA) 19 November 1991<br>Columns 4-9, Figure | 1-4, 8, 12<br>11 |

[X] Further documents are listed in the continuation of Box C

[X] See patent family annex

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**C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT**

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|---|---|---|
| | WO 96/36895 A (UNIVERSITY OF SOUTHAMPTON) 21 November 1996 | |
| X | Pages 2-9, Figure 1 | 1-2, 4-5, 9-10, 12-17 |
| Y | | 11 |
| | WO 97/26570 A (BRITISH TELECOMMUNICATIONS PUBLIC LIMITED COMPANY) 24 July 1997 | |
| X | Pages 5-7, 9, Figures 1-2 | 1-2, 4-5, 9-10, 13-15 |
| Y | | 11 |
| | WO 97/21120 A (THE UNIVERSITY OF SYDNEY) 12 June 1997 | |
| Y | Whole document | 11 |

## INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
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| Patent Document Cited in Search Report | | Patent Family Member | | | | | |
|---|---|---|---|---|---|---|---|
| US | 5388173 | EP | 736201 | WO | 9517705 | | |
| US | 5066133 | WO | 9207289 | | | | |
| WO | 9636895 | AU | 56990/96 | EP | 826161 | NZ | 307598 |
| WO | 9726570 | EP | 866989 | EP | 875013 | WO | 9722023 |
| WO | 9721120 | AU | 76868/96 | EP | 873529 | | |

END OF ANNEX